frequency it is seen that they coincide with the diagonal from the O/O corner; also that the entries of minimum frequency are disposed symmetrically on either side of that diagonal and converge towards the same corner. Consequently, the existence of spurious correlation is manifest here. If B be the constant, and A and C the variables, the general results will of course be the same.

Secondly, let both A and B be constant and equal to I, and C the only variable; then there are only three possible combinations of A/C and B/C. In one of them both values are equal to I, in another to I/II, and in the third to I/III, all of which lie along the diagonal from (O, O), and thus testify to intimate correlation.

Lastly, let C be the only constant and equal to 1. Then A/C, B/C, become A and B, and the table of frequency of their various combinations is that shown in Table I and by the large figures in fig. 1, whose symmetrical disposition in all directions proves that there is no correlation.

"Report to the Committee of the Royal Society appointed to Investigate the Structure of a Coral Reef by Boring." By W. J. Sollas, D.Sc., F.R.S., Professor of Geology in the University of Dublin.

Received December 31, 1896,—Read February 11, 1897.

Prefatory Note by Professor T. G. Bonney, D.Sc., LL.D., F.R.S., Vice-Chairman of the Committee.

In presenting, as desired by the Committee, Professor Sollas's report on the attempts to ascertain, by boring, the structure of the atoll of Funafuti and on other investigations simultaneously undertaken, I avail myself of the opportunity of expressing the gratitude which is felt by its members to our friends in New South Wales, who have given such real and substantial help, especially by the loan of machinery and skilled workmen, in putting the project into execution; and among them chiefly to Professor Anderson Stuart (who has been practically another secretary in Australia), Professor Edgeworth David, Mr. W. H. J. Slee (Chief Inspector of Mines), and Sir Saul Samuel (the Agent-General of the Colony in England). I shall venture also to acknowledge gratefully the services of Captain Field and the officers of H.M.S. "Penguin," and the unstinted labour which has been given by Mr. W. W. Watts, F.G.S., our Secretary in London, in carrying out our plans. In conclusion, may I express, speaking for myself, my earnest hope that another attempt will be made to determine the true structure of an atoll. I think, however, that our experience on this occasion shows that the attempt can be

much more easily made, and with a far greater probability of success, if Australia instead of England be the base of operations, and I trust that before long the colony of Sydney will initiate an expedition, and we shall co-operate with them as cordially as they have done with us.

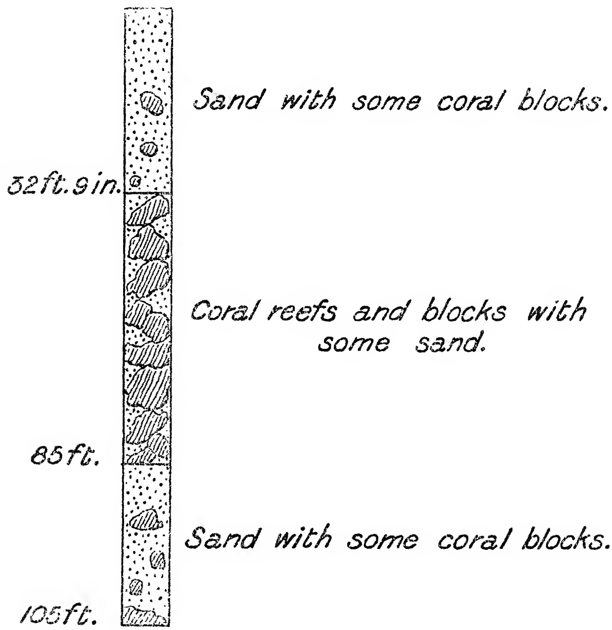
Report by Professor Sollas, D.Sc., LL.D., F.R.S.

H.M.S. "Penguin" having come to anchor in the lagoon of Funafuti on the afternoon of Thursday, the 21st of May, Captain Field at once landed with Lieutenant Dawson, Ayles (the foreman of the boring party), and myself, and we proceeded to make arrangements for our work on the island. A site for boring was chosen near the sandy beach of the lagoon, conveniently situated for the landing of gear, less than half a mile to the south and west of the village of Funafuti, and near the village well, which supplies a small amount of brackish but drinkable water. The work of landing was commenced the next morning, and completed by May 26. The erection of the boring apparatus was at once taken in hand, and on June 2, twelve days after our arrival on the island, all was in readiness for commencing operations. On June 3 the 6-inch tubes were driven into the sand, and by June 6 they had been advanced 30 feet; the 5-inch pipes were then entered and everything made ready for inserting the diamond crown and commencing to drill on Monday, June 8. On June 10 it was arranged that the work should proceed by shifts, so that the drilling might be carried on continuously day and night. During the first shift the crown had been advanced 20 feet, making the total depth then attained 52 feet 9 inches; during this shift fragments of highly cavernous coral rock were brought up in the core barrel from a depth of between 40 and 50 feet.

On June 11, a depth of 85 feet having been reached, it was found necessary to ream the hole preparatory to lining, and by June 15 the necessary reaming and lining had been completed. Up to this, although we had been somewhat disappointed at our slow rate of progress, occasioned partly by the unfavourable nature of the ground and partly by the frequent failure of our machinery, we had anticipated nothing worse than the possibility of finding our allotted time exhausted before we had reached a depth of 1000 feet; but now, on setting the crown to work, it very soon ceased to advance, and Ayles shortly afterwards came to me to announce that, in his opinion, the boring was a failure. Nevertheless, some further progess was subsequently made, and on Tuesday, June 16, a depth of 105 feet was attained. It then became once more necessary to ream and line the hole. Attempts to ream were continued all through Wednesday and Thursday but without success, sand poured into the hole and the reamer could not be driven through it. Efforts were made to remove

the sand by a sand-pump, but proved unavailing, the sand flowing in faster than it could be pumped out. Ayles assured me that it was impossible to descend another foot, and that he considered further labour as time and money thrown away. We decided therefore to abandon this borehole, and to recommence operations on another site, if possible in solid rock.

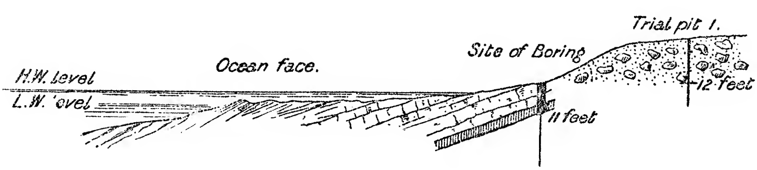
The structure of the ground passed through in the abandoned borehole was as follows:—



Although I knew of many places where solid rock forms the surface of the ground, it was very difficult to find one to which we could transport our machinery, the difficulties of landing on a rocky shore rendered several promising spots inaccessible by sea, while the absence of wheeled vehicles or even wheels, and the nature of the ground, seemed to put transportation by land out of the question.

At last, however, Mr. Hedley pointed out to me a portage called Luamanif, and used by the natives for dragging their canoes from the lagoon to the seaward side of the island, which at this place is very narrow, about 70 yards across. As this seemed a good landing-place, I submitted it to the consideration of Captain Field, who, after a personal examination, agreed that we might safely make use of it. Ayles and his party were then set to

work to sink trial pits on the line of the portage, one of these, situated 70 feet from the high-water mark on the seaward face of the reef, was sunk 12 feet through sand and blocks of coral, when operations were brought a close owing to the influx of sea-water at high tides. Two other pits were then commenced nearer the sea and a little to one side (north) of the portage, at the margin of the solid platform of rock, which extends down to the growing edge of the reef and which is covered by the sea at high-water. These passed through sand and fragments of coral. In the most northern of the two pits the sand was somewhat consolidated, and so, proceeding a few yards further north, as far in that direction as it would have been possible to transport our machinery, we opened another pit, which was sunk for a depth of 11 feet through fragments of coral, crystalline coral limestone, and partly consolidated sand. The bottom of the pit was 2 feet below the seaward margin of the reef, and as we were not inconvenienced by an influx of sea-water and Ayles was of opinion that the rock would "stand," we decided to make our new venture at this spot. Taking into consideration the difficulties of transporting our apparatus, I do not think a more favourable locality could have been chosen; it was close to the very edge of the rocky platform, which is so hard that Darwin, speaking of a similar platform in the case of another reef, says "I could with difficulty and only by the aid of a chisel procure chips of rock from its surface;" and as near the sea as it was prudent or even possible to go. Indeed, we had at first some doubt as to whether our pumping pipes would "live" in the surf of the ocean margin, and feared that the high-water spring tides might inundate the shaft; our fears in these respects, however, proved to be groundless.



Captain Field and myself were impressed with the need of additional boring apparatus, and he proposed that Ayles should go to Sydney to see if it could be procured. I gave much anxious consideration to this project, and discussed it with my colleagues, Messrs. Hedley and Gardiner, and with Ayles. The information I received from Ayles was not encouraging. He stated that we should require a complete equipment of lining tubes from 10 inches down to $2\frac{1}{2}$ inches in diameter, that 10-inch tubes were not to be had in Sydney, and that even if we succeeded in obtaining all the

appliances we required, the success of the boring would even then by no means be assured.

For a doubtful result I did not feel justified in incurring the certain increase in our expenditure which a journey to Sydney would have involved; the question of time had also to be considered, for had Ayles gone to Sydney we should on his return have been commencing our boring at or after the date the Committee had considered it would have been completed. Finally, it appeared that the new locality we had chosen for our work offered fair prospects of success.

The shaft already sunk to a depth of 11 feet was then timbered with Pandanus logs, and arrangements made for carrying down a hole by jumping with a 6-inch chisel. Ayles spoke of getting as far as 50 feet by this means, and then lining the hole with 6-inch tubes, but after sinking 4 feet he declared it impossible to proceed further in this way, the chisel could not be made to continue sinking in a straight line, the labour was too exhausting, and progress very slow. It was decided, therefore, to begin boring, Ayles being very hopeful, as the hole "stood" well. On Thursday, June 25, we accordingly made arrangements to shift our boring gear to the new site, and by Saturday, June 27, this work was completed, chiefly by native labour, and at a cost of about £10. The boilers were rolled along the beach, the rest of the machinery taken by water, and all subsequently dragged, rolled, or carried across the portage. Lieutenant Waugh lent us valuable assistance, during the absence of the "Penguin," in this work.

Boring was commenced on Friday, July 3, and by 5 o'clock we had sunk another 4 feet; progress then became rapid, and on Saturday evening, when work was knocked off, we had descended in all 46 feet. Very little "core" was obtained, however, and at times the boring bit met with very little opposition as it advanced, seemingly passing through a vacant space. Since the water pumped into the hole no longer flowed out above, but found its way out by some communication with the sea below, it was impossible to determine whether or not some sand might have been present. It was clear, however, that the coral rock through which the "bit" advanced was highly cavernous.

On Monday the hole became filled with fallen fragments and some sand, it was evident, therefore, that the sides would not hold, and so recourse was had to lining; by Thursday, July 9, the hole had been reamed and lined down to 45 feet, and the work of boring was resumed. On pumping, we had the satisfaction of seeing the water flowing out of the top of the hole, but our joy was short-lived, for, on Monday, June 13, the water was again lost. On Tuesday, July 14, we had reached 65 feet, passing for the last 20 feet through sand and coral. Subsequently we attained a depth of 72 feet, and could then proceed

no further. We worked all Thursday and Friday with the sand pump, but with no success; the bottom of the hole was surrounded by quicksand containing boulders of coral, and as fast as the sand was got out, so fast it flowed in and faster. The water pumped down disappeared through the sand, boring and *à fortiori* reaming was impossible, and the tubes could not be driven owing to the interspersed boulders. Had the tubes been provided with steel driving ends we might have forced them down; as it was, the effect of driving them was simply to curl in the lower end. Had we been provided with 4-inch tubes we could have made a fresh start, and might have descended another 30 or 40 feet, but even then ultimate success would not have been ensured, for the chance of meeting again and again with intermixed sand and coral remained always open, and every such encounter would have required lining tubes of diminished calibre.

Baffled in all our endeavours, and no other part of the island offering more hopeful prospects of success, we had no alternative but to abandon the undertaking, and on July 30 we were taken from the island in the "Penguin," and returned to Fiji. On landing there we had the mortification to learn that additional apparatus was then on the way to Funafuti, our friends in Sydney having with great generosity at once despatched machinery for driving in sand on receipt of a letter I had sent informing them of the failure of our first borehole. We had had no reason to expect such spontaneous assistance, and even had we been fortunate enough to have remained on the island till the machinery arrived, we should probably not have accomplished the object we had in view, though we might possibly have carried the borehole down to a depth of about 400 feet.

A very free communication must have existed between the borehole and the sea, for whenever a big roller broke upon the reef the rods lifted, and after the lining had been withdrawn, water spurted out of the borehole with the fall of every wave. The open nature of the reef is further indicated by the fact that the sea water rises with every tide to fill certain depressions, which occur in many places in the middle of the island; as the tide ebbs this water flows away down fissures, often so rapidly as to form little whirlpools.

Wherever I have seen the reef growing it has always presented itself as clumps or islets of coral and other organisms with interspersed patches of sand, and the borings would seem to indicate that it maintains this character for a very considerable depth and possibly throughout. The structure of the reef appears indeed to be that of a coarse "sponge" of coral with wide interstices, which may be either empty or filled with sand.

As regards the nature of this "sand," it is important to observe that it does not consist of coral *débris;* this material and fragments

of shells forming but an insignificant part of it; calcareous algæ are more abundant, but its chief constituents are large foraminifera, which seem to belong chiefly to two genera (*Orbitolites* and *Tinoporus*). It covers a considerable area of the islands, and has accumulated during the memory of the inhabitants to such an extent as to silt up certain parts of the lagoon. This and the abundant growth of corals and calcareous algæ, such as *Halimeda*, lead to the belief that the lagoon is slowly filling up.

A suggestion has recently been made that more light is likely to be thrown on the history of atolls by a study of ancient limestones in the British Isles than by boring in existing reefs. The first essential, however, for such a study would appear to be a knowledge of the structure of living atolls, for, without this, the identification of others forming a part of the earth's crust, might remain more or less a matter for conjecture. So far as the structure of Funafuti has been proved by borings, it is scarcely what a field geologist might have anticipated, and if deposits of a similar nature and origin should have been encountered in, say, the mountain limestone, it is doubtful whether, previous to the borings in Funafuti, their interpretation would have been easily reached.

While the boring has proved a failure, the other objects of the expedition have been attained with complete success. Messrs. Hedley and Gardiner have made a thorough investigation of the fauna and flora, both land and marine. Dr. Collingwood has obtained a good deal of information of ethnological interest, and we all have brought home a fairly complete collection of native implements and manufactures. A daily record was kept of maximum and minimum temperature, and of the readings of the dry and wet bulb thermometers.

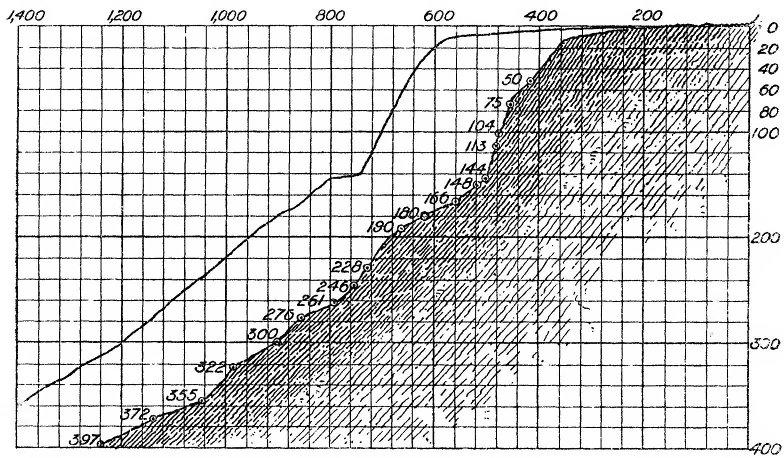
The most important contribution, however, and one that I think must, in certain details, greatly modify our views as to the nature of coral reefs, is afforded by the investigations of Captain Field. Never before have soundings, both within and without an atoll, been so closely and systematically made, and the results seem to me commensurate with the care and pains that have been taken to secure them. Four series of soundings, "Sections" as they are termed on board the "Penguin," have been run from the seaward face of the reef outwards. How close together the soundings were made is shown in the following table which Captain Field has kindly permitted me to copy from his order book:—

Depth	0— 40	fathoms every	10	yards.
,,	40— 70	,,	20	,,
,,	70—100	,,	30	,,
,,	100—150	,,	40	,,
,,	150—200	,,	50	,,

Depth	200—300 fathoms every	60 yards.	
,,	300—400 ,,	70	,,
,,	400—500 ,,	80	,,
,,	500—600 ,,	90	,,
,,	600—700 ,,	100	,,
,,	700—800 ,,	200	,,

The profiles obtained by the four series are closely similar, and, as regards one important feature, almost identical. This is the sudden change in slope that occurs at or about 140 fathoms. Speaking generally, one may describe Funafuti as the summit of a submerged conical mountain, the base of which, at a depth of 2,000 fathoms, is a regular ellipse, 30 miles long by 28 miles broad. It rises with a very gentle slope, which gradually grows steeper as it ascends, till from 400 to 140 fathoms it has an angle of 30°; at 140 fathoms an

Section D.



Two profiles of the ocean face of Funafuti. Vertical and horizontal scales identical. Figures on the vertical co-ordinate refer to fathoms, on the horizontal to yards.

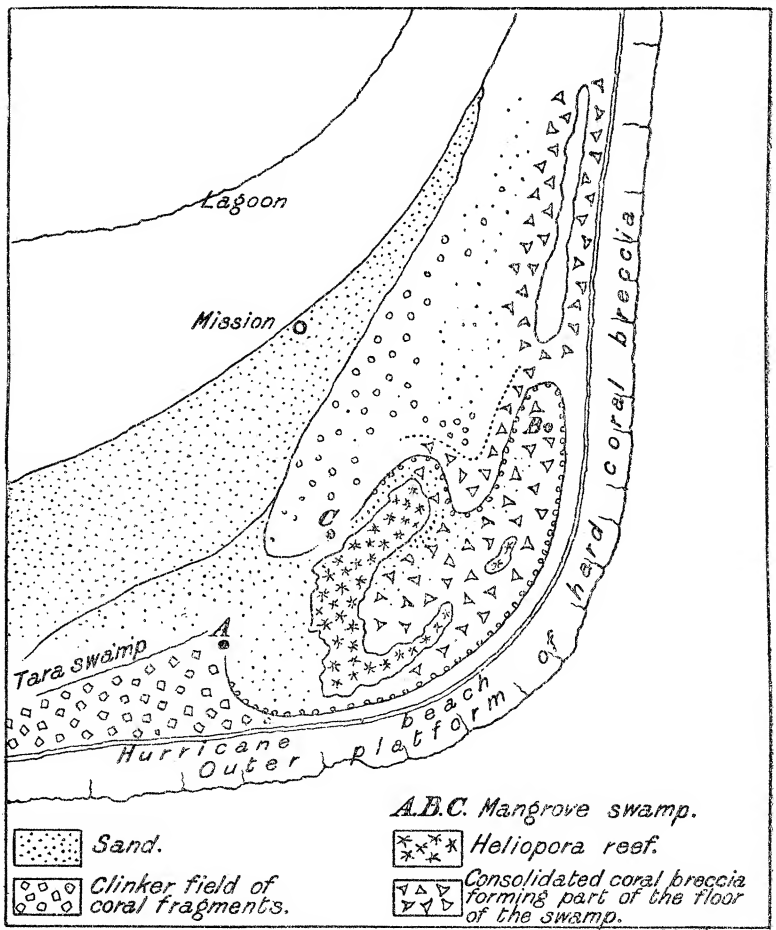
The curve on the left is supposed to commence 200 yards to the left of the zero point.

abrupt change occurs, and the slope becomes precipitous, making an angle of from 75° to 80° for the greater part of its course, till it passes into the shallow flats of the growing reef. It is difficult to resist the impression that it is the upper 140 fathoms (840 feet) which represents the true coral reef. A convex curvature of the profile between 166 and 261 fathoms is probably a talus, produced by an accumulation of coral *débris*.

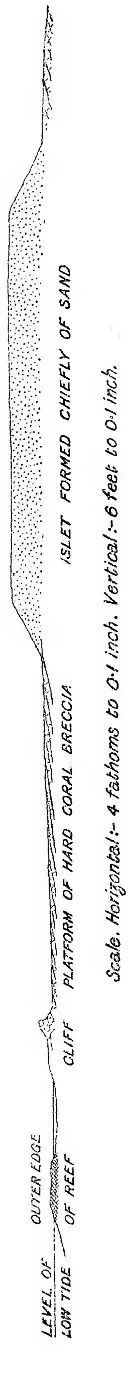
The conical mountain below the 140 fathoms line, with its parabolic slope, is suggestively similar to a volcano; but, if so, its crater must have been immense, 10 miles across at least. A volcano, 12,000 feet in height, with a crater 10 miles in diameter, is, however, not an unknown phenomenon; within the limits of the Pacific we may cite Haleakala, in Maui, Sandwich Islands, as closely comparable.

A part of my work while on the island was the construction of a geological sketch map, part of which is shown below; its interest chiefly centres in a broad expanse near the Mission Station, where the two narrow limbs of the island meet, or, if it be preferred, whence

Corner of Funafuti, showing Mangrove Swamp and Heliopora Reef.



they extend. Towards the seaward side this broad corner is occupied by a mangrove swamp, the floor of which is formed by a dead coral reef, constituted almost wholly of two species, one a massive Porites, and the other *Heliopora cœrulea.* For a great part of the day this floor lies bare and dry, the frayed ends of the Heliopora standing like broken reeds, 6 inches above its surface, and the great clumps of Porites forming a series of stepping stones of equal height. Neither of these corals stands long exposure to the air; on Funafuti they require constant submergence, and we are thus led to regard their upper surface as marking what was at one time the level of low tide in the swamp; but since the present level of low tide is below the level thus indicated, some change must have occurred in the level of low tides. Not necessarily an elevation of the reef: Darwin has admirably discussed this explanation, and it is quite conceivable that some change in local conditions, such as the exclusion of the sea by the growth of the hurricane beach, may have produced a local alteration in the height of the tides. The swamp communicates with the sea by pits in its floor, which enter subterranean channels running seawards. These passages are so narrow that the tide rises and falls in the swamp much more slowly than in the open sea. To determine whether any change of level has taken place, it thus becomes necessary to compare the highest and lowest water level of the swamp with that of the sea or of the lagoon. I accordingly levelled across the island from the lagoon to the sea, crossing the swamp on the way, and found that the high-water level at spring tides is 1 foot 10 inches below high water (spring tides) of the lagoon, so that given free access of the sea, the Heliopora reef would be covered 1 foot 10 inches deeper than at present, but it is now submerged from 10 inches to 2 feet 2 inches at high-water springs, and would accordingly be submerged from 2 feet 8 inches to 4 feet, with free access of the sea. The range of spring tides is at least 6 feet, as I learn from Lieutenant Dawson, but I am not quite sure that an extreme range of 9 feet 8 inches has not been observed. Taking, however, the smaller number, it becomes clear that for a considerable part of the day, the reef would be exposed to the air. It is not likely that under these conditions the corals would continue to live, and I think, therefore, that the reef must have undergone some slight elevation, to the amount, perhaps, of 4 feet. This conclusion is in accordance with Dana's view, and is supported by observations on some other features of the island, such, for example, as the occurrence of an interrupted line of low cliffs, sometimes passing into a series of pinnacles, generally about 4 feet in height, as measured from low water level. In the annexed section the cliffs are farther from the land than is usually the case. These cliffs consist of a consolidated breccia of coral fragments, and are now in process of denuda-



SECTION THROUGH THE ISLET OF PAVA, FUNAFUTI.

tion, as is the coral platform which extends from them, up to and under the hurricane beach. This breccia was probably formed and cemented together when the reef stood at least 4 feet lower than at present, and was produced by the breakers driving fragments of corals from the seaward edge of the reef into the lagoon, as they are now doing over the isthmuses, submerged at high tide, which connect the several islets of the atoll together.

If it should prove true, as I do not doubt, that one of the latest episodes in the history of the reef has been an elevation of, say, 4 feet, then in the immediately antecedent stage, the reef must have been awash, or, perhaps, wholly submerged, and the present terrestrial fauna and flora must have reached it subsequent to its elevation, as sea drift, or have been introduced by human agency.

In conclusion, I would add that to myself the soundings obtained by Captain Field appear to support Darwin's theory of coral atolls; there remains, however, one very important branch of the subject which stands in need of renewed investigation, and this is the bathymetrical limit to coral life.

Not till I had obtained a close acquaintance with the difficulties of dredging on the steep sides of an atoll did I recognise on how frail a basis our accepted conclusions rest. It is a task difficult enough to get up corals from the lagoon in comparatively shallow water; from the sides of the reef it is well nigh impossible. To obtain dead corals from great depths proves little; living corals are generally found with dead associates, and the latter are the more readily detached and brought to the surface.

The weight of the evidence we already possess is admittedly in favour of a comparatively shallow bathymetrical limit, but much remains to be done before we can speak of any limit as definitely ascertained.